APPARATUS COMPRISING AN ATOMIZER AND METHOD FOR ATOMIZATION

Statement of Related Cases

[0001] This application is a continuation-in-part and claims priority of PCT/US02/32595, filed October 11, 2002, which claims priority of U.S. 60/328,654, filed October 11, 2001, both of which cases are incorporated by reference herein.

Field of the Invention

[0002] The present invention relates to atomizers, methods for atomization, and systems that include atomizers.

Background of the Invention

[0003] Atomization is a process by which a liquid is dispersed into very fine droplets. The droplets in an atomized liquid are often less than 200 microns in diameter and can be as small as about 10 microns. Atomized liquids are used in many applications including, for example, fire-suppression, fuel-combustion, coating processes, pharmaceuticals, and metallurgy, to name but a few.

[0004] Atomized liquid is generated using an atomizer. A variety of atomizer designs exist. One common type of atomizer is the "Hartman" atomizer. In a Hartman-type atomizer, a high-velocity (supersonic) gas stream impinges on a cavity resonator. The resonator abruptly brakes the supersonic gas stream, which results in the creation of shock waves. A stream of liquid exits the atomizer in the vicinity of the shock waves. The energy in the shock waves atomizes the liquid. Examples of Hartman atomizers include the atomizers disclosed in U.S. Patents 6,390,203 and 4,408,719. The atomizer that is disclosed in U.S. Patent 6,390,203, which was developed by one of the present inventors, is discussed below.

[0005] The atomizer disclosed in U.S. Patent 6,390,203 is reproduced in Figure 1 as atomizer **100**. That atomizer includes rod **102**, inner casing **104**, outer casing **110**, and head **116**. Annular gas feed channel **106** is defined between rod **102** and inner casing **104**. The gas feed channel leads to annular gas nozzle **108**. Annular liquid feed channel **112** is defined between inner casing **104** and outer casing **110**. The liquid feed channel leads to annular liquid nozzle **114**. Resonator **118** is defined as an annular channel within head **116**. The resonator is spaced apart from and situated in opposition to gas nozzle **108**.

[0006] In operation, a subsonic flow of gas (*e.g.*, nitrogen, *etc.*) is directed to gas feed channel **106**. Gas is discharged from gas nozzle **108** at the speed of sound. Once discharged, the gas expands and its speed becomes supersonic. The gas is abruptly decelerated by resonator **118**, which causes acoustic oscillations (*i.e.*, shock waves) in atomization zone **120**. The oscillations cause liquid (*e.g.*, water, *etc.*) that is delivered to atomization zone **120** through liquid nozzle **114** to atomize. A mist of water droplets exits atomizer **100** through ring-shaped outlet **122**.

[0007] In a Hartman atomizer, the amount of liquid that is atomized is proportional to the amount of shock waves produced. It is convenient, then, to express the efficiency of a Hartman atomizer in terms of the amount of shock waves that are produced by a given volume of gas (passing through the atomizer). To calculate the efficiency (according to this defnition), the power, P_{gj}, (*i.e.*, energy per time) of the gas jet issuing from the nozzle is calculated. This calculation is readily performed knowing the rate of gas discharge and its density. Shockwave power, P_{sh}, is measured in known fashion and the percentage efficiency of the atomizer is calculated by obtaining the ratio of the power in the shockwave to the power of the gas jet and then multiplying that ratio by one hundred:

[1] $Eff = (P_{sh} / P_{gj}) \times 100$

[0008] The efficiency of standard Hartman atomizers, such those described in U.S. Patents 6,390,203 and 4,408,719, is usually relatively low, being in a range of about five to eight percent.

[0009] The prior-art includes alternatives to Hartman-type atomizers, but these other atomizers typically exhibit even lower efficiency than Hartman atomizers. For example, U.S. Patent 4,205,788 discloses a "swirl" atomizer. In this type of atomizer, a swirl chamber imparts rotary motion to a gas. The swirling gas is passed through a nozzle, which intensifies the degree of swirling and generates some acoustic oscillations, which atomize a liquid. The swirling gas contains relatively little energy and these atomizers operate at a very low efficiency of about 0.5 to about 1.0 percent.

[0010] In another type of atomizer, liquid is atomized via a substantially stationary decrease in compression. In this type of atomizer, as exemplified by U.S. Patent 5,495,893, bubbles of pressurized gas are dispersed in a liquid. The gas-liquid mixture is then exposed to a substantially instantaneous reduction in pressure (such as is caused by a sudden, large increase in flow area). (*See* also, U.S. Patent

6,142,457.) The reduction in pressure causes the gas bubbles to rapidly expand and atomize the liquid. The mixture is then accelerated to supersonic velocity through a nozzle. As the mixture decelerates to sonic velocity, shock waves are produced, which further decrease the size of the droplets in the atomized liquid.

[0011] The efficiency of "stationary-decrease-in-compression" atomizers is typically within a range of about 2 to 3 percent. The reason for the low efficiency is that these atomizers produce relatively few shock waves per unit time, since oscillation does not occur as in a Hartman atomizer.

[0012] In circumstances in which an unlimited amount of gas and liquid is available for use in an atomizer, the benefits of a higher-efficiency atomizer are not immediately clear. But in circumstances in which gas and liquid availability is severely limited, the benefits of increased efficiency are manifest. An example of an application in which these resources are strictly limited — and in which atomizer efficiency is therefore very important — is fire-suppression in aircraft.

[0013] Many existing fire-suppression systems for aircraft use a fluorine-containing material (*e.g.*, Halon®). This material has been associated with the depletion of the ozone layer and has been banned by the international community for general use. Aircraft are, however, exempt from this ban and are allowed to continue to use Halon®-based fire-suppression systems until a viable alternative is developed. One potential alternative to Halon®-based systems is a system that uses an atomizer to generate a water mist. The water mist, along with a quantity of nitrogen gas that atomizes water to create the mist, is discharged to suppress a fire. (*See*, *e.g.*, U.S. Patent 6,390,203.) There are strict weight allowances on aircraft, and nitrogen and water are not exempt from them. As a consequence, it is critically important that a nitrogen/water mist fire-suppression system includes a relatively more-efficient atomizer, which will use less nitrogen (thereby saving weight) to provide a given quantity of water mist than a relatively less-efficient atomizer.

[0014] Notwithstanding the foregoing, there has been little progress made toward improving the efficiency of atomizers. It might be supposed that since atomizers have such a relatively uncomplicated structure, little can be done to improve their efficiency. Or, in view the relatively sophisticated understanding of the fluid dynamics of gas flow and the production of shock waves that prevails in the art, it might be supposed that all that can be done to improve atomizers has been done. These suppositions would, however, be incorrect.

[0015] While simple in outward appearance, an atomizer, such as a Hartman atomizer, is extraordinarily complex in terms of the fluid dynamic and acoustic behaviors that govern its operation. And to the extent that these behaviors are understood, the prior art has demonstrated little ability to apply this understanding to the development of higher-efficiency atomizers. But it is one thing to understand the theories, it is quite another to apply them to develop a specific atomizer configuration that exhibits improved efficiency. A better explanation for any lack of progress toward the development of higher-efficiency atomizers is simply the complexity of the problem. Notwithstanding sophisticated modeling techniques, this problem is so complex that improvements are at least as likely to come from empirical studies and observation as from theoretical consideration of the problem.

Summary

[0016] The illustrative embodiment of the present invention is an atomizer, a method for atomization, and a system that includes an atomizer.

[0017] In some embodiments, an atomizer in accordance with present invention operates at substantially higher efficiency than most known atomizers, and in particular most Hartman-type atomizers. For example, while typical prior-art Hartman atomizers operate at about 5 to 8 percent efficiency, embodiments of the present atomizer operate at efficiencies of at least 10 percent, preferably at least 15 percent, more preferably at least 20 percent, and most preferably at an efficiency of 25 percent or more.

[0018] A reason for this higher efficiency is the significantly greater instability that develops within the supersonic gas flow of the atomizers described herein. This greater instability is evidenced by a substantially greater amount of pulsation in the gas flow. (The words "pulsation" and "pulsations" are used interchangeably in this specification.) The "amount" (*e.g.*, frequency, intensity) of these pulsations determines the efficiency at which energy in the gas flow is converted to acoustic oscillations (*i.e.*, shock waves). That is, to the extent that there is a greater amount of pulsation in the flow of gas, more of the energy in the gas will be converted to shock waves. In other words, more pulsations mean higher efficiency. The reasons why greater instability is developed in the gas flow of the atomizers disclosed herein are given below.

[0019] Furthermore, in some embodiments, atomizers in accordance with the illustrative embodiment operate at lower gas pressure and lower liquid pressure than most atomizers. Low-pressure operation is particularly desirable for certain fire-suppression applications. A further benefit of an atomizer in accordance with the illustrative embodiment is its structural simplicity. In particular, in some embodiments, the atomizer comprises only three parts. This reduces manufacturing costs, improves reliability and decreases the coefficient of variation in atomizer performance.

[0020] An illustrative method for atomization comprises:

- receiving a flow of gas;
- accelerating the flow of gas to supersonic velocity;
- generating an amount of pulsation in the flow of gas that is sufficient to enable the conversion of at least ten percent of the energy of the flow into shock waves; and
- delivering liquid to the shock waves at an atomization zone.

Notwithstanding the implied order of the operations of the method, as listed above, at least some of the operations or sub-operations that are responsible for generating the pulsations in the flow of gas occur prior to accelerating the flow of gas to supersonic velocity.

[0021] The method requires the creation of a "sufficient" amount of "pulsation" in the supersonic flow of gas. Both the amplitude and frequency of the pulsation contribute to satisfying the requirement of a "sufficient" amount. The pulsation of the gas is created by destabilizing the flow of gas within the atomizer. In accordance with the illustrative embodiment, one or more operations are employed or conditions are created to destabilize the gas flow or otherwise promote pulsation, including, without limitation:

- generating a sufficient amount of transverse components of speed in the gas;
- affecting the flow of gas so that its velocity profile is characterized by an inflection point; and
- operating at a gas pressure that is within the range of about 21 psig to about 52 psig.

[0022] As used herein, the phrase "**transverse component(s) of speed**" is used to describe a particle of gas that has a non-axial vector of motion, wherein the axial direction is defined to be the direction in which the bulk of the gas flows at given location within the atomizer. A non-axial vector is described by two components, a "transverse" component, which is orthogonal (*i.e.*, 90 degrees) to the axial direction and an "axial" component that is aligned (*i.e.*, 0 degrees) with the axial direction. The particle's net vector is determined, of course, by the relative magnitudes of the two components of speed. In other words, any particle of gas that is moving in a non-axial direction has a transverse component of speed.

[0023] In the present context, a "sufficient" amount of transverse components of speed is an amount that results in an inflection point in the cross section of the velocity profile. (These two conditions, then, are not independent of one another.) The amount of transverse components and the direction of those components contribute to the establishment of the desired velocity profile (*i.e.*, the presence of an inflection point). As is known by those skilled in the art of fluid dynamics, for inviscid (*i.e.*, no viscosity - purely mechanical) flow, the velocity profile must contain an inflection point somewhere in its cross section to be instable.

[0024] With regard to operating pressure, it has been found that it is particularly advantageous to perform the atomization at a gas pressure within the atomizer that is within a range from about 21 psig to about 52 psig. Gas pressures falling within this range have been found to be unusually effective for the efficient creation of shock waves. To account for pressure drop, gas inlet pressure to the atomizer should be at least about 25 psig, since a critical pressure of 21 psig directly upstream of an internal gas nozzle is required for developing sonic flow, apart from any efficiency considerations. In some embodiments, the gas inlet pressure is advantageously limited to about 55 psig (to provide a maximum pressure of about 52 psig within the atomizer).

[0025] Although the exact mechanism is somewhat uncertain, it is believed that within this range of pressure, a second resonance — a pressure-based resonance that appears to be unrelated to the resonance frequency of the resonator — is created. This additional "resonance" is responsible for more instability and more pulsation. As previously indicated, the pulsation of the gas determines the efficiency by which the energy in the supersonic gas flow is converted in acoustic oscillations or shock waves. To the extent that there is more pulsation (frequency or amplitude) in

the gas flow, the intensity of the resulting shock waves increases. And if the intensity of the resulting shock waves increases, more liquid is atomized or the liquid is atomized into smaller droplets.

[0026] The destabilizing operations or conditions listed above are promoted by providing an atomizer that, by virtue of its configuration, *etc.*, exhibits one or more of the following attributes:

- a compression factor, μ, that is within a range of about 5 to 50 and, and in some embodiments, is in a range of about 5 to about 30;
- a conicity angle, α, that is in a range of about 50 to about 80 degrees,

among any others. In the illustrative embodiment, these attributes are defined with respect to certain structures within the atomizer; namely, a gas cavity and a gas nozzle. These structures are described briefly below and more fully later in the Detailed Description section of this specification.

[0027] Briefly, the compression factor, μ, is a ratio of the cross-sectional area for flow at the inlet of the gas nozzle and the cross-sectional area for flow at the outlet of the gas nozzle:

[2] $\mu = A_F^I / A_F^O$

The conicity angle, α, refers to the angle by which the nozzle tapers from its inlet to its outlet.

[0028] In the illustrative embodiment, the gas cavity is disposed immediately upstream of the gas nozzle. In some embodiments, the (axial) direction of the opening that leads into the gas cavity is substantially orthogonal to the (axial) direction of the exit from the gas cavity (and entrance to the gas nozzle). As a consequence, the direction of the bulk flow of gas into the gas cavity and the direction of the bulk flow of gas out of the gas cavity are different from one other. This contributes to the generation of transverse components of speed. Furthermore, the gas cavity and gas nozzle or both, as appropriate, are dimensioned to provide a compression factor that is within the desired range (*i.e.* 5-50) and the gas nozzle is shaped to provide a conicity angle that is within the desired range (*i.e.*, 50-80 degrees).

[0029] As long as the flow of gas is at or above a critical pressure of about 21 psig in the gas cavity, the flow of gas reaches sonic velocity at the exit of the nozzle and reaches supersonic velocity as the flow expands beyond the nozzle. As the gas exits the nozzle, a flow pattern that exhibits a sufficient amount of transverse components of speed and a velocity profile that exhibits an inflection point are established. Pulsation or unstable gas flow results.

[0030] This supersonic, unstable gas flow is directed toward a cavity resonator that is spaced apart from and opposes the gas nozzle. In some embodiments, the gas flow pulses at a rate of at least about 18 kHz — 18,000 times per second — in accordance with the resonance frequency of the cavity resonator. As the unstable, supersonic gas slams into the resonator, shock waves are generated. The shock waves propagate toward an atomization zone.

[0031] Liquid, which is delivered to the atomization zone, is atomized into droplets by the shock waves. The size of the ensuing liquid droplets is a function of the frequency of the shock waves, the sound pressure resulting from the shock waves, the gas density and the liquid surface tension. Beyond these dependencies, droplet size can be adjusted up or down by simply increasing or decreasing the rate of flow of the liquid through the atomizer.

[0032] Again, a key reason why an atomizer in accordance with the illustrative embodiment operates at higher efficiency than those in the prior art is that:

- it generates substantially more pulsation than prior-art Hartman atomizers. This is because atomizers in accordance with the illustrative embodiment are configured with instability-enhancing features not generally found in the prior art. As previously described, these features include, without limitation, the aforementioned gas cavity with directionally-skewed in-flow and out-flow, an appropriate value for a compression factor, and a suitable conicity angle of the gas nozzle, as defined above.
- Furthermore, in some embodiments, in addition to the use of one or more of these instability-enhancing features, the atomizer is operated within a specific range of pressure (about 21 to 52 psig) that has been found to further increase atomization efficiency.

[0033] The present atomizers are suitable for use in a variety of applications. One such application is in a low-pressure, fire-suppression system. A low-pressure system is generally lighter, safer, and less expensive to construct, install and maintain than a high-pressure system. Consider, for example, an application in which a fire-suppression system is used in the cargo hold of an aircraft. Motions of the aircraft (*e.g.*, during take-off, landing, and turbulence, *etc.*) can impart stresses to the various piping connections within a fire-suppression system. These stresses can result in breaches of the piping connections. Breaches in a high-pressure line, such as will be found in a high-pressure fire-suppression system, can cause catastrophic damage on an aircraft. Breaches in a low-pressure line are of far less concern.

[0034] For fire-suppression applications, the gas used in the atomizer is typically nitrogen and the liquid is typically water. The system includes ample supplies of water and nitrogen (*e.g.*, from bottles, from a nitrogen generator, *etc.*), piping to connect the water and nitrogen supplies to the atomizers, detectors for detecting a fire condition, and actuating capabilities to start a flow of nitrogen and water when a fire condition is detected.

[0035] Further details concerning atomizers, atomization methods, and a system incorporating an atomizer in accordance with the present invention is provided in the following Detailed Description and the appended Drawings.

Brief Description of the Drawings

[0036] **Figure 1** depicts prior-art Hartman atomizer **100**.

[0037] **Figure 2A** depicts method **200** in accordance with the illustrative embodiment of the present invention.

[0038] **Figure 2B** depicts sub-operations of one of the operations of method **200**.

[0039] **Figure 3A** depicts an illustration of transverse components of speed within a flow of gas.

[0040] **Figure 3B** depicts a cross section of a velocity profile of the flow of gas, wherein the profile has an inflection point.

[0041] **Figure 4A** depicts a block diagram of atomizer **400** in accordance with the illustrative embodiment of the present invention.

[0042] **Figure 4B** depicts a block diagram that shows illustrative sub-elements **404** and **406** of element **402** of atomizer **400**.

[0043] **Figure 4C** depicts a block diagram that shows illustrative sub-elements **408** and **410** of sub-elements **404** of atomizer **400**.

[0044] **Figure 5A-5C** depicts an illustrative implementation of sub-elements of Figure 4B, wherein the elements are implemented as a gas cavity, gas nozzle and cavity resonator.

[0045] **Figures 5D-5F** depicts various flow configurations for the implementation of Figures 5A-5C, as a function of conicity angle of the gas nozzle.

[0046] **Figure 6A** depicts an exploded, cross-sectional view of atomizer **600**, which is a specific implementation of atomizer **400** in accordance with the illustrative embodiment of the present invention.

[0047] **Figure 6B** depicts a cross-sectional view of atomizer **600**.

[0048] **Figure 7** depicts a cross-sectional view of central core **640** at line **5-5** in Figure 6B in the direction shown.

[0049] **Figure 8** depicts a perspective view of atomizer **600**.

[0050] **Figure 9** depicts a bottom view of atomizer **600** showing a gas outlet nozzle and water outlet nozzles.

[0051] **Figure 10** depicts the flow of liquid and gas through atomizer **600**.

[0052] **Figure 11** depicts some important dimensions and parameters of atomizer **600**.

[0053] **Figure 12** depicts the three pieces that compose illustrative atomizer **600**.

[0054] **Figure 13** depicts some dimensions of atomizer **600**.

[0055] **Figure 14** depicts a system for fire suppression that incorporates one or more of the present atomizers.

Detailed Description

I. Overview

[0056] The illustrative embodiment of the present invention is an atomizer, a method for atomizing, and a system that incorporates an atomizer. The atomizer is useful in a variety of industrial applications, including fire suppression systems, fuel-

combustion processes, coating processes, to name a few. The atomizer operates with two fluids: a gas and a liquid. Fluid selection is application dependent, although the liquid is typically water, which is cheap, readily available, non-toxic and environmentally friendly. The water or other liquid used in the present atomizers can include additives for any of a number of purposes. A partial listing of water-based solutions suitable for use with the present atomizer includes: water solutions of insecticides, herbicides, bactericides, fertilizers, medications, as well as melted metals (for the production of fine metal powder). The gas is usually nitrogen, for at least some of the same reasons (relatively safe, readily availability, *etc.*) that water is used as the liquid. Other suitable gases include, without limitation, carbon dioxide, argon and mixtures thereof.

[0057] Although simple in structure, the theory underlying the operation of atomizers such as those described herein is quite complex. A thorough understanding of the atomizer's operation involves an awareness of fluid dynamic and acoustic behaviors that are beyond the scope of this specification. Most importantly, such theory is not particularly germane to an understanding of the present invention and would tend to distract rather than enlighten. Those skilled in the art will be aware of the relevant theoretical considerations, which, in conjunction with the disclosure provided herein and in the appended drawings, will enable them to make and use the illustrative embodiments and other variations that are consistent therewith. To the extent that some theoretical details are believed to be useful for pedagogical purposes, they will be provided.

[0058] As previously discussed, atomizers that are described in this specification function by generating shock waves that atomize a liquid. The shock waves are generated by creating instability in a supersonic flow of gas and then abruptly braking the gas flow, such as with a cavity resonator. In some embodiments, atomizers described herein operate at substantially higher efficiencies than those in the prior art. The reason for this is that the present atomizers incorporate a variety of instability-inducing features that are capable of destabilizing the gas to a far greater extent than atomizers in the prior art. Furthermore, in some embodiments, the present atomizers are operated within a particular range of pressure that has been found to promote the creation of shock waves.

II. Method in Accordance with the Illustrative Embodiment

[0059] FIG. 2A depicts method **200** in accordance with the illustrative embodiment of the present invention. Method **200** includes the operations of:

- receiving a flow of gas (operation **202**);
- accelerating the flow of gas to supersonic velocity (operation **204**);
- generating an amount of pulsation in the supersonic flow that is sufficient to enable conversion of at least ten percent of the energy in the flow into shock waves (operation **206**); and
- delivering liquid to an atomization zone (operation **208**).

[0060] Operation **202** typically involves receiving a subsonic flow of gas. In accordance with operation **204**, the flow of gas is accelerated to supersonic velocity. This typically involves a change in cross-sectional flow area or a change in pressure or both.

[0061] In accordance with operation **206**, pulsations are generated in the now supersonic flow of gas. More particularly, an amount (frequency and/or intensity) of pulsation is generated that is sufficient to enable the conversion of at least ten percent of the energy in the supersonic gas flow to shock waves.

[0062] Shock waves are produced by abruptly braking the pulsating, supersonic flow of gas, as is described in more detail later in this specification. Liquid is delivered to an atomization zone where it is atomized by the power of the shock waves.

[0063] Figure 2B depicts sub-operations **210** and **212** of operation **206**. These sub-operations are responsible for generating a suitable amount of pulsation in the supersonic flow of gas.

[0064] Operation **210** requires generating transverse components of speed within the flow of gas. These "transverse components," which generally appear after the gas is accelerated to supersonic velocity, flow in directions other than the direction of the bulk flow of gas. This is illustrated in Figure 3A, which depicts flow of gas **302**. The direction of the bulk flow is along axis **1-1**, which is referred to herein as the "axial" direction. Transverse components of speed **304** are depicted within bulk flow **302** as components that flow in directions other than along axis **1-1**. The transverse components of speed ultimately create shear flow. The presence of shear flow is a necessary condition to create the instability that leads to pulsation in the flow of gas. While most atomization methods will create some amount of transverse components

of speed, they generally create far less than the atomization methods and the atomizers that are described herein. And this is a reason for the relatively low efficiency of prior art atomization methods and atomizers.

[0065] Operation **212** requires affecting the flow of gas such that the velocity profile of the gas includes an inflection point. It is well known (Rayleigh, 1880) that in a shear flow, a necessary condition for instability is that there must be a point of inflection somewhere in the velocity profile $U(z)$:

(3) $d^2U/dz^2 = 0$

This is simply a consequence of the conservation of momentum. Figure 3B depicts two plots **306** and **308** showing average gas velocity in the axial direction across a cross section of a gas flow. Velocity profile **306** is flat and, therefore, is stable. On the other hand, velocity profile **308** includes inflection point **310**, which is required for unstable flow.

[0066] Sub-operations **210** and **212** provide at least two interrelated conditions that are necessary to generate the pulsations required in operation **206**.

[0067] The term "sufficient" is used in operation **206** and impliedly arises in the consideration of operation **210**. In other words, most atomization methods generate transverse components of speed, which lead to pulsations in the flow of gas. The distinction between those prior-art methods, and the present method, at least at the level of specificity of operations **206**, **210**, and **212**, is that most prior-art methods are not capable of generating sufficient transverse components of speed to establish a velocity profile that includes an inflection point. As a consequence, they are not capable of generating sufficient pulsations to achieve an efficiency of ten percent or more, as required for the illustrative method.

[0068] Since both the amount of transverse components of speed, and the direction of those components contribute to establishing an inflection point in the velocity profile, it is impractical to define the modifier "sufficient" in terms of an "amount" of these quantities. Rather, the term "sufficient" is defined with reference to a result, *i.e.*, the amount/direction of the transverse components of speed are sufficient when an inflection point is established in the velocity profile. Furthermore, "sufficient" is also defined with respect to certain structural criteria of a device that carries out the atomization method.

[0069] Two structural (or structural-related) criteria of particular importance relate to conditions at a gas nozzle, which is typically found in devices that carry-out atomization methods. The gas nozzle is typically used to accelerate the flow of gas (as per operation **204**), among other purposes. The aforementioned criteria involve (1) the degree to which the gas flow is compressed as it passes through the nozzle and (2) pertain to the shape of the nozzle. The first criterion, which is the compression factor, μ, should be in a range of between about 5 to about 50, and is advantageously within a range of about 5 to about 30. The second criterion, which is the "conicity angle, α," is advantageously within a range of 50 to 80 degrees. Further details regarding these criteria are provided later in this specification in conjunction with a description of an atomizer in accordance with the illustrative invention.

III. Apparatus in Accordance with the Illustrative Embodiment

[0070] Figure 4A depicts, via a block diagram, atomizer **400**. Atomizer **400** includes arrangement **402** for converting at least ten percent of the energy of a supersonic flow of gas into shock waves and arrangement **412** for conducting liquid to the atomization zone. Arrangement **412** delivers liquid via liquid outlet **414** to atomization zone **416**. Shock waves generated from arrangement **402** propagate to atomization zone **416** and atomize the liquid in known fashion.

[0071] Figure 4B depicts further detail of an embodiment of arrangement **402**. Arrangement **402** comprises arrangement **404** for generating pulsation in the flow of gas and arrangement **406** for abruptly braking the flow of gas. In the illustrative embodiment, arrangement **404** for generating pulsation and arrangement **412** for conducting liquid are contained in body portion **405** of atomizer **400**. As in operation **206** of method **200**, arrangement **404** for generating pulsation must generate sufficient pulsations to enable the conversion of at least ten percent of the energy of a supersonic gas flow into shock waves. As the pulsating, supersonic flow of gas is abruptly braked by arrangement **406**, shock waves are produced. The shock waves propagate toward atomization zone **416** to which liquid is delivered.

[0072] Figure 4C depicts further detail of an embodiment of arrangement **404** for generating pulsations. In the embodiment depicted in Figure 4C, arrangement **404** includes arrangement **408** for generating transverse components of speed and arrangement **410** for affecting the flow of gas so that the velocity profile has an

inflection point. The concept of "transverse components of speed" and the "inflection point" have previously been described in conjunction with method **200**.

[0073] Figure 5A depicts a group of structures that are collectively able to function as an implementation of arrangement **402** (for promoting the conversion of at least ten percent of the energy of an at least sonic flow of gas into shock waves). These structures include gas cavity **GC**, gas nozzle **GN**, and cavity resonator **CR**. Similarly, gas cavity **GC** and gas nozzle **GN** are collectively able to function as an implementation of arrangements **404** (for generating pulsation), arrangement **408** (for generating transverse components of speed), and arrangement **410** (for generating a velocity profile with an inflection point).

[0074] To be suitable as an implementation of arrangement **402**, however, wherein at least ten percent of the energy must be converted to shock waves, the structures must satisfy certain provisos. For example, in some embodiments, gas nozzle **GN** must be appropriately dimensioned and configured to provide:

- a compression factor, μ , that is within a range of between about 5 and about 50, and advantageously within a range of 5 to 30; and
- a conicity angle, α, with a range of 50 to 80 degrees.

[0075] With reference to Figure 5B, for gas nozzle **GN**, compression factor, μ , is given by the ratio of the cross-sectional area for flow at the mouth of the gas nozzle to the cross-sectional area for flow at the outlet of the nozzle. For other nozzle configurations, the compression factor might be expressed somewhat differently. In conjunction with the disclosure provided herein, those skilled in the art will be able to modify the definition of compression factor, as appropriate, to account for changes in the configuration of the atomizer.

[0076] Conicity angle α is defined in Figure 5C. For gas nozzle **GN**, conicity angle α is a measure of the inward taper of the nozzle. It is notable that axis **2-2** of inlet **I** and axis **3-3** through outlet of gas cavity **GC** are orthogonal to one another. As a consequence, the direction of the bulk flow of gas ***G*** into cavity **GC** and the direction of the bulk flow of gas **G** out of gas nozzle **GN** are substantially different. This difference in direction, in conjunction with appropriate selection of compression factor μ and conicity factor α, as detailed above, provide a complete description of an embodiment suitable for promoting the conversion of at least ten percent of the energy of a supersonic flow of gas into shock waves because it is capable of generating the requisite instability (pulsation). This embodiment is capable of

generating the requisite instability because it is capable of generating a sufficient amount of transverse components of speed to establish a velocity profile that has an inflection point. It is also understood that there are certain requirements for resonator **CR** as well, but these are controlled by standard design considerations that are described later in this specification.

[0077] In some other embodiments, in addition to providing the requisite characteristics of gas cavity **GC** and gas nozzle **GN**, the pressure of the gas (at the inlet to the atomizer) is in a range of about 25 to 55 psig. As previously indicated, operating within this range of pressure further increases the efficiency of an atomizer in accordance with the illustrative embodiment of the present invention.

[0078] Figures 5D through 5E provide a generalized depiction of the impact of conicity angle on a flow of gas ***G*** through gas cavity **GC** and gas nozzle **GN**. Specifically, Figure 5D depicts gas nozzle **GN** with a conicity angle α = 0 degrees. Gas ***G*** flows with little deviation through gas nozzle **GN** and does not develop the requisite instability (*i.e.*, too few transverse components of speed are generated). Figure 5E depicts gas nozzle **GN** with a conicity angle α = 90 degrees. This provides too much braking such that the gas flow is not at sonic or greater velocity as it leaves the gas nozzle **GN**. As a consequence, the flow is incapable of creating shock waves. On the other hand, Figure 5F depicts gas nozzle **GN** with a conicity angle that is within the range of 50 to 80 degrees. In this case, gas flow **G** is sufficiently deviated to generate the required shear components downstream of gas nozzle **GN** and to establish the desired velocity profile.

[0079] It will be understood that while Figures 5A-5C depict gas nozzle **GN** having a straight or linear taper, in some other embodiments, the gas nozzle has a different taper. For example, in some embodiments, the gas nozzle is parabolic, has an irregular surface, *etc*. These variations might affect the acceptable range for the conicity angle. Those skilled in the art will be able to determine any such change in the desired range by, for example, changing conicity angle in an exemplary atomizer and observing the affect on the velocity profile (*e.g.*, the velocity profile should satisfy the inflection point criterion). As a consequence, any such deviation in conicity angle from the specified range of 50 to 80 degrees, as a result of modifications to the structure of gas nozzle **GN**, falls within the anticipated scope of the appended claims.

IV. Specific Implementation of an Atomizer in Accordance with the Illustrative Embodiment

[0080] The remainder of this Detailed Description pertains to atomizer **600**, which is a specific implementation of the illustrative embodiment (*i.e.*, atomizer **400**). The structure of atomizer **600** is described in Section IV.A, in conjunction with Figures 6A-6B, 7-9 and 12. In Section IV.B, and in conjunction with Figure 10, the fluid flow through atomizer **600** is described. Design considerations for atomizer **600** are presented in Section IV.C, in conjunction with Figure 11. An example of a working nozzle is provided in Section IV.D. Finally, a system for fire-suppression that employs atomizer **600** is depicted in Figure 13.

IV.A Structure of Atomizer 600

[0081] Figures 6A and 6B depict a side cross-sectional view of atomizer **600** in accordance with the illustrative embodiment of the present invention. For increased clarity, Figure 6A depicts atomizer **600** via an "exploded" view. After the structure of atomizer **600** is described, it will be related to features of illustrative atomizer **400**.

[0082] Referring now to Figures 6A and 6B, atomizer **600** includes casing **602**, central core **640**, and cowling **680**.

[0083] The profile of casing **602**, when viewed in side cross section as depicted in Figures 6A and 6B, is varied or irregular and consists of various line straight line segments (*e.g.*, segments **606**, **608**, *etc.*) that are disposed at different radial distances from central axis **4-4** of atomizer **600**. It will be understood that this portion of the interior of atomizer **600** actually comprises circular cylindrical surfaces. As a consequence, many of the straight segments (*e.g.*, segments **606**, **608**, *etc.*) that are depicted in the cross section are, in actuality, curved segments. Additionally, the profile includes several angled or tapered segments (*e.g.*, segments **614**, **618**, *etc.*). It will be understood that this portion of the interior of atomizer **600** actually comprises circular conical surfaces. For simplicity, these various segments are shown as straight lines and will be referred to as "surfaces." The irregular profile and various surfaces of casing **602** serve several purposes.

[0084] One purpose of the irregular profile and various surfaces of casing **602** is to enable the casing and the central core to securely engage one another. Specifically, surface **604** of casing **602** receives surface **642** of central core **640**. In the illustrative embodiment depicted in Figures 6A and 6B, these surfaces are threaded

for secure, locking engagement. And surfaces **644** and **646** of central core **630** abut respective surfaces **606** and **608** of casing **602**.

[0085] A second purpose of the irregular profile of casing **602** is to define, in conjunction with central core **640**, various cavities and channels, including:

- gas cavity **670**; and
- gas nozzle **672**.

[0086] The irregular profile of the outer surface of casing **602**, in conjunction with cowling **680**, defines the following cavities and channels:

- liquid cavity **690**;
- liquid outlet channels **692**; and
- liquid outlets **694**.

More particularly, surfaces **610** and **612** of casing **602** and a portion of surface **646** of central core **630** define gas cavity **670**. Angled surface **614** of casing **602** and a portion of surface **646** define gas nozzle **672**.

[0087] Opposing and spaced from gas nozzle **672** is resonator **664**, which is an annular channel that is defined by surfaces **646**, **648** and **650** in the portion of central core **656** that extends from casing **602**. In operation, resonator **664** brakes the gas that flows from gas nozzle **672**. As described previously in conjunction with resonator **400**, this braking creates intense oscillations of the gas (shock waves) that drive atomization of the liquid.

[0088] Cowling **680** engages the exterior of casing **602**. In particular, an upper portion of surface **682** of the cowling abuts surface **626** of casing **602**. The cowling and casing are joined by a press fit, or in other ways known to those skilled in the art.

[0089] Liquid inlet **630**, which is disposed at surface **628** of casing **602**, leads to liquid inlet channel **632**. The liquid inlet channel leads, in turn, to liquid cavity **690**. The liquid cavity is defined by surfaces **620**, **622** and **624** of casing **602** and a lower portion of surface **682** and an upper portion of surface **684** of cowling **680**.

[0090] Liquid cavity **690** feeds a plurality of liquid outlet channels **692**, which lead to liquid outlets **694**. As depicted in Figure 7, which is a partial cross-sectional view of casing **602** through line **5-5** and viewed from the top in the direction of the arrows, each liquid outlet channel **692** is defined by groove **796**, which is formed in the surface **618** of casing **602**. When atomizer **600** is fully assembled, a second portion

of surface **684** of cowling **680** covers grooves **796** to form liquid outlet channels **692**. Neither the number nor size of liquid outlet channels **692** is particularly critical to atomizer operation. The liquid outlet channels must simply be capable of passing a desired amount of liquid (*e.g.*, 2 kg/min, 6 kg/min, 10 kg/min, *etc.*) at the prevailing liquid pressure. In most embodiments, there will be between about 4 to 20 liquid outlet channels **692** each having a width of several millimeters (*e.g.*, 2 mm to 6 mm, *etc.*) and a depth of less than a millimeter (*e.g.*, 0.2 mm to 0.6 mm, *etc.*).

[0091] In some prior-art nozzles, such as the ones disclosed in U.S. Patents 4,408,719 and 6,390,203, the water nozzle is configured as a "ring" or annular region that surrounds the gas nozzle. The ring configuration of the water nozzle is dependent upon relatively precise machining and adjustment for proper operation of the atomizer. For example, if the gap that defines the annular nozzle is not uniform around the full circumference of the nozzle, channeling might occur, wherein liquid flows preferentially in the region of the nozzle where the gap is largest. Using grooves **796** to form liquid outlet channels **692** substantially reduces the likelihood of such a problem occurring in atomizer **600**.

[0092] Figure 8 depicts a perspective view of atomizer **600**. Top surface **628** of casing **602**, the exterior of cowling **680**, and a portion of central core **640** are visible in Figure 8. The visible portion of central core **640** includes surface **646** and resonator **664**. Fitting **898** is engaged to liquid inlet **630**. In some embodiments, fitting **898** is used to couple liquid inlet **630** to a hose (not depicted) through which liquid (*e.g.*, water, *etc.*) is supplied to atomizer **600**.

[0093] Figure 9 depicts a bottom view of atomizer **600**. In this view of atomizer **600**, liquid outlets **694**, annular gas nozzle **672**, and bottom surface **656** of central core **630** are visible.

[0094] With reference to Figure 10, atomizer **600** comprises three main parts: casing **602**, central core **640**, and cowling **680**. The use of so few parts generally results in reduced manufacturing cost and improved reliability relative to atomizers that have a greater number of parts. Furthermore, having fewer parts reduces alignment issues such that the consistency of operation from atomizer to atomizer is very consistent (*i.e.*, low coefficient of variation).

[0095] Table 1 below relates some of the structure of atomizer **600** to certain structural features of atomizer **400**.

ATOMIZER **400**	ATOMIZER **600**
Body Portion **405**	Casing **602**, cowling **680**, and upper portion of central core **640**
Arrangement **404** for generating pulsations	Gas cavity **670**, gas nozzle **672**
Arrangement **412** for conducting liquid	Liquid cavity **690**; liquid outlet channels **692**; and liquid outlets **694**
Liquid outlet **414**	Liquid outlets **694**
Arrangement **406** for Braking	Resonator **664**

Table 1: Correspondence Between Atomizer **600** and Atomizer **400**

IV.B Fluid Flow Through Atomizer 600

[0096] Referring now to FIG. 11, which depicts the flow of gas and liquid through atomizer **600**, and with continuing reference to FIG. 6B, gas flows to axially-disposed channel **658** and then passes to axially-disposed channel **660** in central core **640** of atomizer **600**. Radially-disposed apertures **662** in central core **640** enable gas to pass from axially-disposed channel **660** into gas cavity **670**. Gas flows from gas cavity **670** through gas nozzle **672**, which tapers from a maximum width (nearest cavity **670**) to a minimum width (as the gas exhausts toward resonator **664**).

[0097] Liquid is supplied to atomizer **600** at inlet **630**, which is located at a marginal portion of casing **602**. Liquid flows from inlet **630**, through liquid inlet channel **632** to annular liquid cavity **690**. In the illustrative embodiment, in which liquid is provided via a single inlet **630**, liquid cavity **690** provides for a uniformity of flow of the liquid about the circumference of casing **602**.

[0098] Liquid exits liquid cavity **690** through liquid outlet channels **692**. Liquid outlet channels **692** leads to liquid outlets **694**. From the liquid outlets, the liquid enters atomization zone **674**, which is located near the gap between resonator **664** and gas nozzle **672**, but radially outward thereof to the region beneath liquid outlets **694**. The intense oscillation of the gas causes the liquid entering this zone to atomize. This phenomenon is described in further detail below.

[0099] Atomizer **600** is designed for a specific liquid flow rate. Atomizers designed for 2 kilograms/minute, 6 kilograms/minute, and 10 kilograms/minute have been

built and tested. The gas flow rate, in kilograms per minute, is typically in the range of about 0.7 to 1.5 times the liquid mass-flow rate. In other words, for a 2 kg/min atomizer, the gas flow will be in a range of about 1.4 to 3 kg per minute, for a 6 kg/min atomizer, the gas flow will be in a range of about 4.2 to 9 kg per minute, and for a 10 kg/min atomizer, the gas flow will be in a range of about 7 to 15 kg/min.

[0100] A most desirable ratio of the mass flow rate of gas to liquid will generally exist and is application-specific. For example, for fire suppression with water and nitrogen, the gas-to-liquid mass-flow ratio is advantageously about 1.0. But even within the context of fire suppression, this ratio can vary from installation to installation. As a consequence, the gas-to-liquid mass-flow rate is best determined by simple experimentation, using the range provided above as a starting point.

IV.C Design Considerations and Theory

[0101] In this Section, design considerations and theory is presented for atomizer **600**. Some of the information appearing in this Section has been previously presented in conjunction with the description of method **200** and atomizer **400**. It is to be understood that the theory and considerations presented in this Section are generally applicable to the illustrative embodiments (*i.e.*, method **200** and atomizer **400**) unless otherwise noted.

[0102] Several dimensions and parameters are defined below and are depicted in Figure 12 for use in the following description. In particular:

- The conicity angle, α, is the complement of the angle subtended between surfaces **614** and **616** of casing **602**.
- $\mathbf{D_K}$ is the diameter of gas cavity **670**.
- $\mathbf{D_S}$ is the diameter of central core **640**.
- $\mathbf{D_N}$ is the diameter of gas nozzle **672**.
- δ is the width of the mouth of gas nozzle **672**.
- **H** is the height of resonator **664**.

[0103] As long as the pressure of gas within gas cavity **670** exceeds a critical pressure (typically 21 psig), gas is discharged from gas nozzle **672** at sonic velocity (*i.e.*, Mach 1), as is desirable.

[0104] Gas cavity **670** should have a compression factor, μ, at gas nozzle **672** that within a range of about 5 to about 50, and is advantageously in the range of about 5 to about 30, wherein the compression factor is given by the relation:

$$[4] \qquad \mu = (\mathbf{D_k}^2 - \mathbf{D_s}^2) / (\mathbf{D_n}^2 - \mathbf{D_s}^2)$$

The magnitude of the compression factor, μ, affects:

- the ability to uniformly fill gas cavity **670**; and
- the gas flow through gas nozzle **672**.

Regarding the latter effect, this pertains to the generation of transverse components of speed as well as an inflection point in the velocity profile.

[0105] Increasing the compression factor improves some aspects of atomizer performance. But increases in the compression factor will increase pressure drop across gas nozzle **672**. This will require an increase in the gas inlet pressure. As gas pressure in atomizer exceeds about 52 psig, efficiency of the atomizer will drop to low levels. It is expected that at a compression factor of about 50, the efficiency of the atomizer (as previously defined) will be at about 10 percent. Furthermore, while there are many applications in which the increase in pressure is of no consequence, there might be applications where maintaining low gas-supply pressure is important (*e.g.*, fire-suppression in aircraft, *etc.*).

[0106] As the gas discharges from gas nozzle **672**, it expands, and its speed becomes supersonic. The gas is abruptly braked by resonator **664**, which results in shock waves, which create relatively high sound-pressure levels in atomization zone **674**.

[0107] It is known that there exists some threshold sound pressure that is required to begin dispersing liquid into droplets (*i.e.*, atomization). This threshold depends upon a variety of factors, including the surface tension of the liquid being atomized, the shape of the initial "jet" of liquid issuing from liquid outlets **694**, and the presence of a gas flow. The sound pressure level required for efficient atomization of water, for example, is in the range of 160 to 170 dB, which corresponds to a sound intensity in the atomization zone in the range of about 1-10 W/cm^2. Thus, in accordance with the illustrative embodiment, the sound pressure levels in atomization region **674** are at least 160 dB when the liquid being atomized is water.

[0108] For a near-wall ring jet, such as occurs in the configuration of atomizer **600**, the unsteady modes that are formed as a result of the deceleration of the gas caused

by an empty resonator are realized at Strouhal numbers, *Sh*, that are close to the quarter-wavelength resonance. That is:

[5] $Sh = \Delta/\lambda = 0.21$ to 0.23

where: Δ is cell length of the supersonic jet; and
λ is wavelength and $\lambda = c/f$ (c is the speed of sound in the gas and f is the generation frequency).

[0109] The cell length, Δ, is proportional to the width of the nozzle gap δ and also depends upon both the pressure, $\boldsymbol{P}$ of the supplied gas (advantageously within a range of about 25 to 55 psig) and the transverse curvature of the out-flowing jet of gas. For a near-wall ring jet, cell length is given by the expression:

[6] $\Delta = (1.1\, \boldsymbol{D_n} - 0.08(\boldsymbol{D_s})^2 - 0.15\, \boldsymbol{D_s}) \times (\boldsymbol{P} - 0.9)^{1/2}$

[0110] The (jet) curvature parameter is determined by the ratio between the diameter $\boldsymbol{D_s}$ of central core **630** and the diameter $\boldsymbol{D_n}$ of gas nozzle **654**:

[7] $R = \boldsymbol{D_s} / \boldsymbol{D_n}$

The curvature parameter determines the compressibility of the ring jet in the radial direction. That is, it is an indication of how much the jet deviates from a planar jet. In some embodiments, such as those in which atomizer **600** is used in conjunction with a fire-suppression system, the curvature parameter, *R*, should be within the range of about 0.8 to about 0.9. This is a relatively high value for the curvature parameter. Atomizers for use in applications that require a very fine mist at a very small discharge rate (*e.g.*, delivery of medications to new-born babies, *etc.*) will typically have a lower value for the curvature parameter, typically about 0.2.

[0111] For all ranges of the curvature parameter, *R*, the Strouhal numbers are obtained for:

[8] $\delta = (0.03 \leftrightarrow 0.055)\lambda$.

[0112] The relationship between δ and λ is quite complex since wavelength (or frequency) is a function of gas pressure, resonator parameters, gas jet curvature and other parameters. This is accounted for by a constant that is multiplied by λ and which falls in the range of 0.03 to 0.055. This range for the constant is used for all values of the curvature parameter, *R*.

[0113] The atomization process depends not only on the sound pressure level, but also on the frequency of the sound. In particular, the size of the resulting liquid

droplets decreases with increasing frequency of acoustic waves and with increasing sound pressure. A simplified expression for predicting the diameter, d, of an equivalent spherical small drop of atomized liquid at about sound level of about 169 dB is given by:

[9] $d = 2 \times \{(6\pi\ s)/[\rho_L(2f)^2]\}^{1/3}$

where: s is liquid surface tension;
ρ_L is liquid density; and
f is acoustic frequency.

[0114] While the size of droplets that are produced from an actual atomizer will tend to vary somewhat from the values predicted from expression [9], this expression provides a good starting point for design purposes. Once an atomizer design is established, droplet size is readily varied, as desired, by simply changing the liquid rate. For example, for a given shock wave intensity, reducing the liquid rate will reduce droplet diameter. Conversely, increasing the liquid rate will increase droplet diameter. It has been found that to obtain water droplets in the size range of 50 to 90 microns, which is a useful range for fire suppression among other applications, frequency must be within the range of about 16 to 20 kHz.

[0115] The frequency of acoustic oscillations is a function of the height **H** of resonator **664** and the width δ at the mouth of gas nozzle **672**. The required droplet dimensions (*e.g.*, 50-90 microns) can be achieved by using a resonator having height ***H*** that is determined by the relation:

[10] $\boldsymbol{H} = (3 \leftrightarrow 5)\delta$

since the necessary sound pressure levels of 160-170 dB can be obtained only for these values of ***H***. It is believed that, among other influences, the height of the resonator affects the structure of the near-wall gas ring jet, which determines the frequency and intensity of shock waves. This relationship is quite complex, and, in expression [10] above, is accounted for by an empirically-determined constant, which falls within the range of 3 to 5 inclusive.

[0116] It is known that as the sound pressure level in the atomization region increases, the efficiency of atomization increases. It is also known that as the instability of the gas jet increases, relatively higher sound-pressure levels are generated in the atomization region. As previously described, to create the requisite instability requires the presence of sufficient transverse components of speed and a

velocity profile that contains an inflection point. In atomizer **600**, this instability is promoted by a combination of at least some of the following factors: appropriate gas pressure (between about 21-52 psig at gas cavity **670**), judicious design of gas cavity **670**, as well as appropriate selection of values for the compression factor μ, (between about 5 to about 50) and the conicity angle α (between about 50 to about 80 degrees).

[0117] In this context, consider the structure of gas cavity **670**. The gas flowing into gas cavity **670** is moving in a direction that is substantially different from the direction of the bulk gas flow leaving gas cavity **670**. As a consequence, and in conjunction with the pressure factor and conicity angle, the trajectories of the gas particles change sharply. This generates transverse components of speed as the gas leaves gas nozzle **672**.

[0118] Tests were conducted to compare the performance of atomizer **100** with atomizer **600**. The results of the tests showed that when the conicity angle, compression factor, and gas pressure were within the specified range, the atomization efficiency of atomizer **600** was as high as about 26 percent, as compared to an efficiency of about 5 percent for atomizer **100**. The intensity of the shock waves in atomization region **694** of atomizer **600** was 4 dB higher than that achieved in atomizer **100**.

IV.D Dimensions of an Embodiment of Atomizer 600

[0119] Atomizers consistent with the illustrative embodiment have been built and test. The dimensions of one such atomizer, as referenced to Figure 13, are given below. This atomizer was operated at the conditions given below with an efficiency exceeding 25 percent. It is noted that the operating range of this atomizer is, in fact, broader than the tested range of flow rate and pressure.

Liquid:	Water	Flow rate:	2 kg of water/min	Pressure: 5 psig
Gas:	Nitrogen	Flow rate:	1.8 to 2.3 kg/min	Pressure: 35-49 psig
D_{CL}:	70.0 mm	D_{GI}:	12.7 mm	
D_{CA}:	60.0 mm	D_{AG}:	10.0 mm	
D_{WC}:	28.0 mm	D_{RG}:	3.0 mm	(12 equally-spaced apertures)
D_K:	22.0 mm	D_{LI}:	10.0 mm	
D_R:	16.7 mm	D_{LO}:	Depth: 0.3 mm	(6 equally-spaced grooves)
D_N:	15.0 mm		Width: 4.0 mm	
D_S:	13.6 mm			

IV.E System for Fire-Suppression Using Atomizer 600

[0120] As previously indicated, there are many uses for the present atomizer. One use is in conjunction with a system for fire suppression. An illustrative fire-suppression system **1400** is depicted in Figure 14.

[0121] Fire-suppression system **1400** includes two atomizers for protecting area **1416**, such as atomizers **600**. Each atomizer **600** is supplied with gas from gas source **1402** via piping **1406**. Similarly, the atomizers are supplied with liquid from liquid source **1408** via piping **1412**.

[0122] Detector **1414** is capable of detecting an indication of fire (*e.g.*, temperature, smoke, *etc.*) When fire is detected, detector **1414** sends signals to control valves **1404** and **1410** to begin respective flows of gas and liquid to atomizers **600**. Those skilled in the art will be able to engineer fire-suppression systems to meet any of a variety of needs. *See*, for example, USP 6,390,203.

[0123] In this Specification, numerous specific details are disclosed in order to provide a thorough description and understanding of the illustrative embodiments of the present invention. Those skilled in the art will recognize, however, that the invention can be practiced without one or more of the specific details, or with other variations of the illustrative methods, materials, components, *etc.* In some instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of the illustrative embodiments.

[0124] It is understood that the various embodiments shown in the Figures are illustrative representations, and are not necessarily drawn to scale. Reference throughout the specification to "one embodiment" or "an embodiment" or "some embodiments" means that a particular feature, structure, material, or characteristic described in connection with the embodiment(s) is included in at least one embodiment of the present invention, but not necessarily in all embodiments. Consequently, appearances of the phrases "in one embodiment," "in an embodiment," or "in some embodiments" in various places throughout the Specification are not necessarily referring to the same embodiment. Furthermore, the particular features, structures, materials, or characteristics can be combined in any suitable manner in one or more embodiments.

[0125] Furthermore, it will be understood that the above-described embodiments are merely illustrative of the present invention and that many variations of the above-described embodiments can be devised by those skilled in the art without departing

from the scope of the invention. For example, in conjunction with the description of the illustrative embodiments — method **200** and atomizer **400** — and with a specific implementation thereof — atomizer **600** — it is expected that those skilled in the art will be able to develop other specific variations that are consistent therewith. It is therefore intended that such variations be included within the scope of the following claims and their equivalents.